TITLE: Optoelectronic Components and Integration Devices: From Concepts to Applications

Optoelectronic Components and Integration Devices: From Concepts to Applications

D. Jäger and A. Stöhr
Gerhard-Mercator-Universität Duisburg
ZHO - Optoelektronik
Lotharstrasse 55, D-47057 Duisburg, Germany

e-mail: Stoehr@oe.uni-duisburg.de
D.Jaeger@oe.uni-duisburg.de

SUMMARY

The field of optics-microwave interactions can generally be defined as the study of high-speed photonic devices operating at microwave, millimeterwave or even THz frequencies and their use in microwave or photonic systems. In this multidisciplinary field at the interface between microwave techniques, ultrafast electronics and photonic technologies, typical investigations include, for example, high-speed and microwave signal generation, processing and conversion as well as the distribution and transmission of microwave signals via broadband optical links. From pioneering experiments in the 70's, this field of microwave photonics has paved the way for an enabling novel technology with a number of innovative and commercially important applications.

This paper is intended to give an overview on this multidisciplinary field of microwave and millimeterwave photonics addressing specifically high speed optoelectronic components and their integration technologies and giving a glance on a few key microwave applications.

The first chapter gives as an introduction an overview on the field of microwave and millimeterwave photonics and its significance for different microwave techniques. The second chapter is devoted to the principles of microwave optical interaction devices starting with the basics of optically vertical and optical waveguide structures. Moreover, lumped elements as well as traveling wave devices are discussed furtheron. The photonic microwave component family includes photodetectors, laser diodes, modulators, mixers, etc. where different physical interactions can be employed. In particular, recent advances in electroabsorption (EA) devices such as electroabsorption modulators (EAM) and electroabsorption photodetectors (EAD) as well as EA transceivers (EAT) and photomixers (EAX) are discussed in chapter three together with the results from experiments. The fourth part addresses optoelectronic integration techniques such as monolithic integration of different functions but also fiber chip coupling techniques. It is followed by a few interesting examples of photonic microwave signal processing components and modules in chapter five. The sixth chapter is particularly devoted to basic characteristics of microwave optical links and in the last chapter several examples of optical microwave system applications are presented.

1. INTRODUCTION

Within the last decade the field of optics-microwave interactions has attracted growing interest worldwide. The specific term of microwave photonics was introduced in 1991 and used to describe novel optoelectronic components based upon the interaction of traveling optical and microwaves [1,2]. In the following, the merging of microwave and photonic

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technologies was foreseen to be a new approach for future fiber radio communication systems where the RF signal is transmitted over optical carriers [3]. Since then the field of RF optoelectronics and photonics rapidly broadened: Since 1996 International Topical Meetings on Microwave Photoncis (MWP) are being held annually [4] and 1995 was the first year of an IEEE MTT Special Issue on Microwave Photonics now being published regularly [5].

Microwave photonics is an innovative multi- and interdisciplinary field combining and transfering different technologies. In particular, microwave technologies are used and employed in photonics and photonic technologies are utilized in microwave techniques. Moreover, in specific areas novel synergistic concepts have been developed.by merging both technologies which particularly holds for the field of optoelectronics as their interface. As a result of ever increasing frequencies the term microwave stands here for GHz or THz frequencies in the frequency and equivalently for ps- or fs-time scales in the time domain.

This paper is intended to give an overview on together with recent results ranging from devices and technologies to some specific systems under investigation. In particular, the following topics will be addressed by way of key examples of the synergetic mixture of the two technologies involved: (i) Ultrafast photonic components such as optical modulators and detectors with special emphasis on traveling wave devices and including integration technologies. (ii) Concepts and examples of microwave signal processing by way of using photonic technologies. (iii) Broadband and analog optical links for high-speed interconnects. (iv) Microwave photonic systems based upon the merging of microwave and optical technologies.

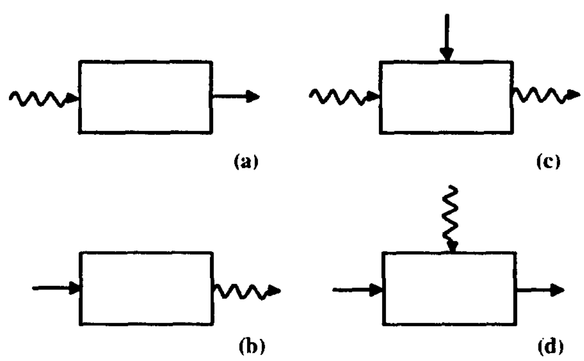

Fig. 1 Optoelectronic device family: Basic microwave-optical interaction devices: (a) Photodetector, (b) light emitting or laser diode, (c) optical modulator with electrical control, and (d) electrical modulator/device with optical control [1,2,6,7]

2. CONCEPTS OF MICROWAVE PHOTONIC DEVICES

Recent advances in the development of high speed optoelectronic devices together with the broadband and low loss transmission capability of optical fibers have in large part been responsible for the global growth of broadband communications. In particular, rapid progress has been made in the development of photodetectors and modulators that may be the key elements in the future ubiquitous high speed optical internet where the optical fiber is coming closer and closer to the customer. In the following an overview on the state of the art of ultra-fast photonic components is given with special emphasis on novel electroabsorption devices and, secondly, future trends in this emerging field of technology are addressed.

In Fig. 1 the four basic optoelectronic interaction devices are sketched. Here two types can be recognized: (i) Two port devices as converters between optical and electrical signals: the photodetector (PD) and the laser or light emitting diode (LD or LED) in Fig. 1 (a) and (b), respectively; (ii) Three port devices such as the electro-optical modulator (MOD) or the optically controlled electrical modulator in Fig. 1 (c) and (d), respectively. Please note that the two elements in Fig. 1 (c,d) are a kind of optoelectronic transistor.

Two basic concepts of microwave optical interactions may further be distinguished, see Fig. 2. As can be seen, the difference is due to different propagation directions of the optical wave. In Fig. 2 (a) the optical wave is traveling normally to the semiconductor surface, i. e. parallel to the flow of the electrical charges. This leads to a design condition where the optical interaction length is coupled and related to the distance the charge carriers are traveling. Hence, in a photodetector – as an example - the absorption length cannot be designed independently from the transit time. In Fig. 2 (b) the optical wave is traveling parallel to the surface so the penetration depth is independent from the transit time in the example of the photodetector.

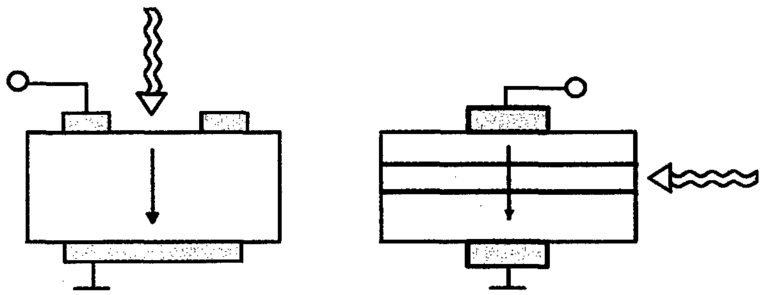

Fig. 2 Microwave optical interaction devices with vertical (a) and horizontal (b) propagation of the lightwave.

For high-speed – electrical - operation electronic devices as shown in Fig. 2 are usually scaled down with respect to the lateral dimensions of the electrical contacts in order to decrease the device capacitance and to decrease correspondingly the RC time constant thus enlarging the cut-off frequency. This procedure is usually limited by power considerations, because smaller devices will lead to smaller operating powers. A solution of this problem is the use of propagation effects of the electrical signal, i. e. to include electrical wave propagation phenomena in the design of the electronic device as well as has been described in [6] and already used in the design of high-speed integrated circuits such as RFICs and MMICs (cf. the well known traveling wave amplifiers), see Fig. 3. According to the design of such traveling wave devices the electrical contacts are realized in form of well known microstrip or coplanar transmission line. As can be seen, in these traveling wave (TW) devices wave propagation effects in the electrical as well as in the optical domain are utilized. The concept is based on the fundamentals of nonlinear optics where from a fundamental point of view interaction always takes place during wave propagation. Obviously, the bandwidths of these elements are not limited by "RC time constants".

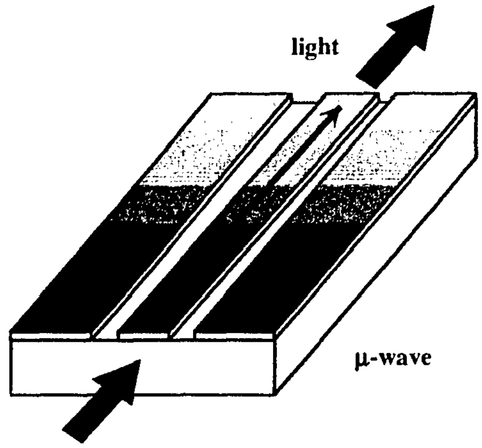

Fig. 3 Traveling wave concept

Moreover, at high frequencies the packaging of high-speed devices or circuits has basically to include electrical wave propagation effects, for example the characteristic impedance of the electrical interconnect. Additionally, the transit time and wave propagation effects of space charges have also to be regarded, especially in the development of high-speed devices. In optics on the other hand, wave propagation is the fundamental physical basis and no lumped elements exist up to now. As a consequence, the design of optical and photonic components usually include optical waveguides (see Fig. 2) and element dimensions are always large with respect to the wavelengths in optics.

In summary, in microwave photonic components an interaction between electrons, holes, electrical fields and photons take place which can be regarded as microwave-optical interactions. Consequently, different technologies meet and may - in a synergetic mixture - be merged in order to develop novel concepts with great advantages.

3. MICROWAVE PHOTONIC COMPONENTS

In the following, some key microwave optical interaction devices are discussed [7-9].

3.1 Electroabsorption modulators – Electroabsorption modulators (EAM) provide a great potential for low voltage operation, large bandwidth and monolithic integration with other components such as laser diodes. In Fig. 4 an EAM is sketched which has been designed for a wavelength of 1.55 μm using InP based semiconductor materials [9,10]. The EAM resembles electrically a pin diode, optically a waveguide is realized where the core is made of a MQW material [11-13] here sandwiched between InP cladding layers for 1.55 μm. The element in Fig. 4 is a lumped element with a coplanar input contact.

Experimental results of different devices are shown in Figs. 5 and 6. In Fig. 5, the characteristics of two digital devices exhibiting a bandwidth of ca 10 GHz and > 40 GHz, respectively, are shown. Note that non-optimised structures have been studied. Alternatively, a traveling wave design leads to a cut-off frequency of > 70 GHz [10]. In Fig. 6 the frequency dependence of a lumped EAM for sensor application and the results of SFDR measurements are plotted.

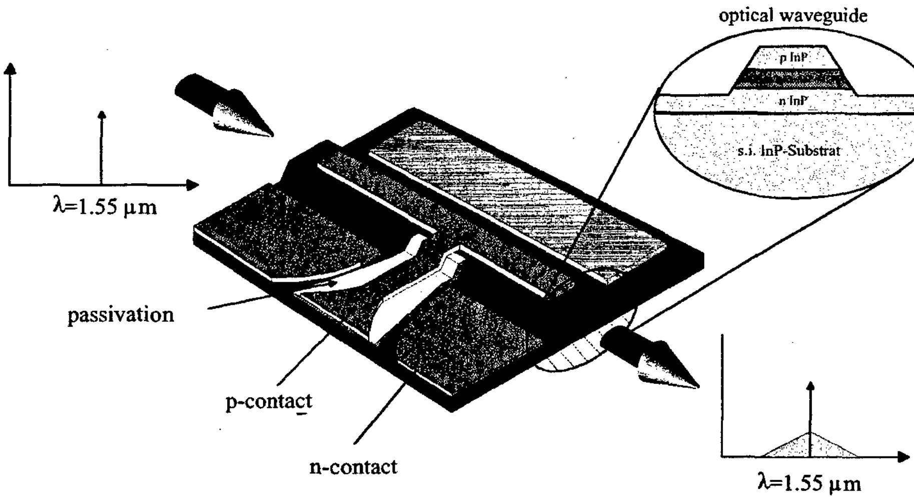

Fig. 4 Electroabsorption modulator (EAM) with cross section

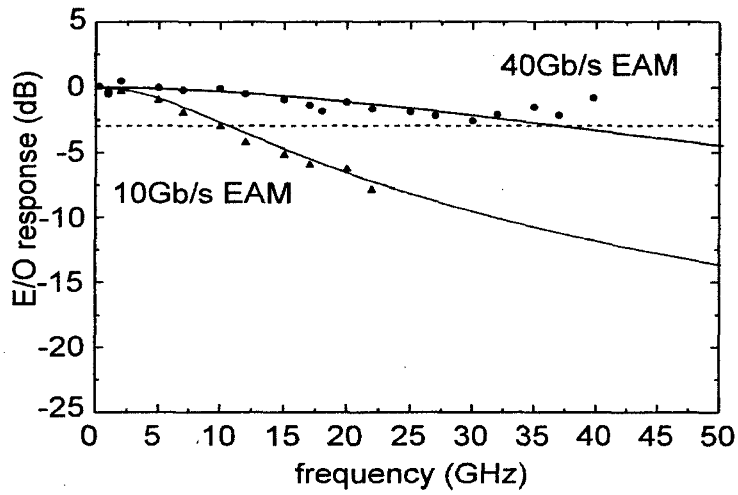

Fig. 5 Modulation of two digital EAMs.

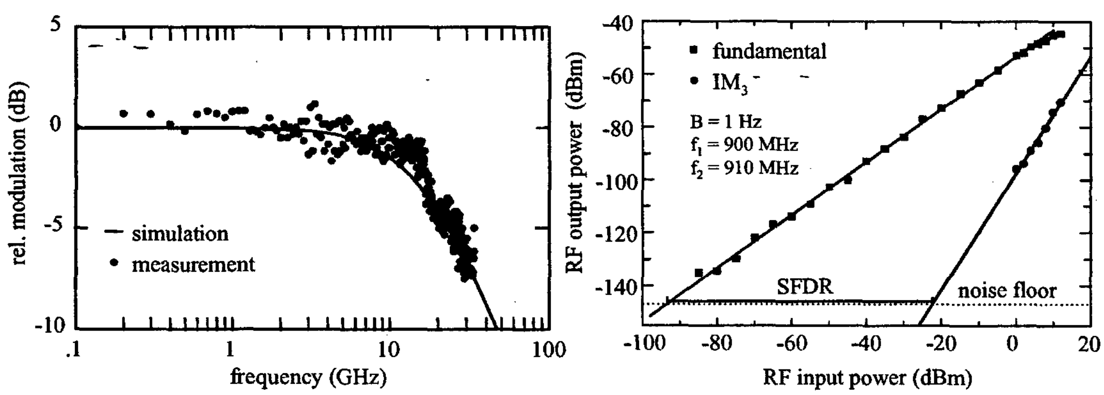

Fig. 6 Frequency dependent modulation of EAMs, (a) lumped element fabricated for sensor applications and (b) measurement of SFDR.

3.2 Electroabsorption detector - Due to the electroabsorption mechanism, i. e. the generation of charge carriers, the EAM can also be used as an – electro-absorptive - photodetector (EAD). A bandwidth of >170 GHz is experimentally demonstrated (Fig. 7) for a traveling-wave pin diode with an active multiple quantum well region. The traveling wave design [14] again includes an optical waveguide and an electrical coplanar transmission line along the optical signal path, see Fig. 3: In this case there is no optical output and no electrical input. Experimentally, a heterodyne set-up has been used where two optical input signals with a corresponding difference frequency are fed into the optical waveguide of the EAD. The photodetection process leads to a photocurrent at the difference frequency measured after down-conversion with a spectrum analyser.

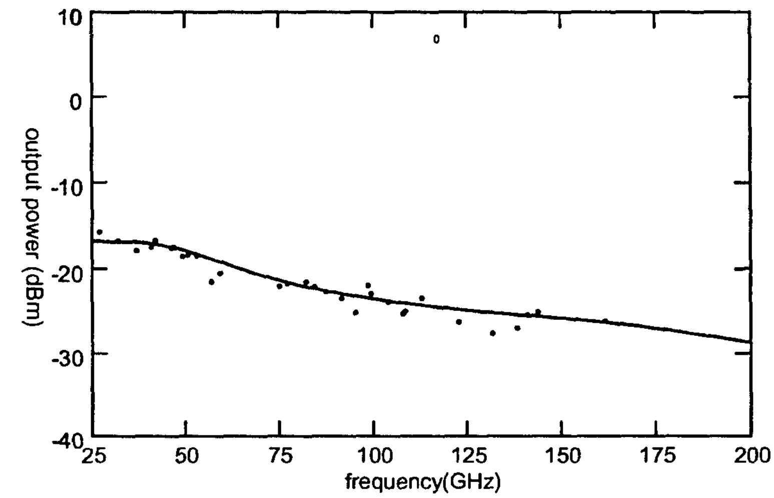

Fig. 7 Frequency response of a traveling-wave 1.55μm photodiode using electroabsorption in the MQW active material of the optical waveguide

Recently, a traveling wave photodetector has been shown to work up to 460 GHz as measured using an SIS mixer (a superconducting Josephson junction) in a THz-antenna system for radio astronomy [15]. Here the photodetector together with the two laser diodes work as a photonic local oscillator

3.3 Electroabsorption mixer - Due to the inherent nonlinearity of the photodetector where the photocurrent is proportional to the square of the electric field of the optical wave, this electroabsorptive device can further directly be employed as a photomixer (EAX). Experimental results for up-conversion at 60 GHz are shown in Fig. 8. In this experiment, again a heterodyne set-up has been used where the two laser diode signals are separated by 60 GHz and one laser diode is additionally modulated at 2.6 GHz. Obviously, the electrical output signal exhibits the RF carrier frequency as well as the side bands due to modulation.

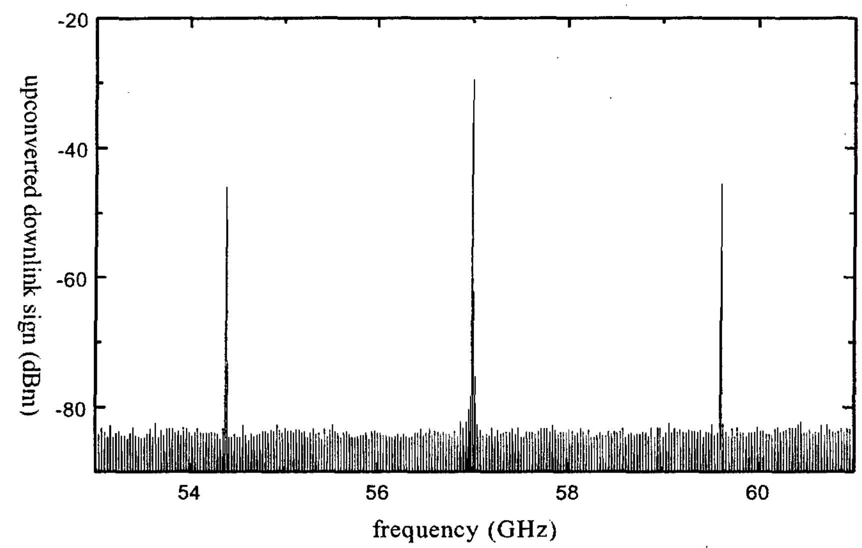

Fig. 8 Optoelectronic mixing in a photodetector, here an electroabsorption photomixer (EAX)

3.4 Electroabsorption transceiver – From the physics of electroabsorption it is concluded that the EAM can simultaneously be used as a modulator and a photodetector where for communication techniques the electrical up- and downlink signals of the device have to be frequency multiplexed. Such a dual function EAM is called electroabsorption transceiver (EAT), [16], Fig. 9. The multifunctional characteristics of such an EAT are finally demonstrated in different fiber wireless systems for broadband communications, see below.

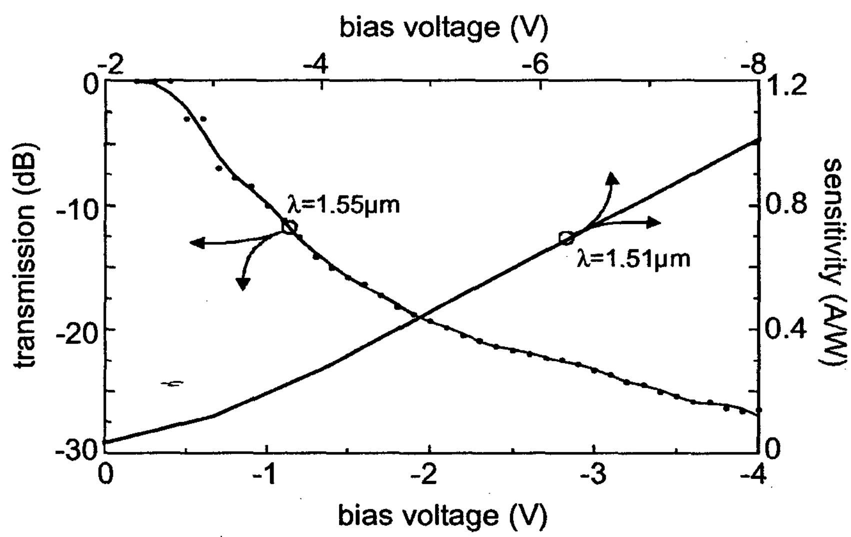

Fig. 9 Photodetection and modulation properties of an electroabsorption modulator. The device is called an electroabsorption transceiver (EAT)

3.5 Electroabsorption SEED element - An EAT can further be used to generate artificial optical nonlinearities such as optical bistability [17] which gives rise to switching, logic and memory effects. From the physical point of view this nonlinearity is caused by the internal feedback between the modulator and the photodetector properties of the device. It has been shown that this characteristic nonlinearity may be useful for multiple-GHz A/D conversion.

3.6 Microwave laser diodes - Up to now laser diodes are usually not made using a special design for microwave applications [18]. In particular, no traveling wave structures are applied although the electrical contact size is already close to the electrical wavelength for frequencies of about 10 GHz. As a result, since several years the cut-off frequency is only about 30 GHz and there is no breakthrough at higher frequencies.

4. OPTOELECTRONIC INTEGRATION TECHNOLOGIES

In an optoelectronic TW device [7,8,9] an optical waveguide (e. g. a strip loaded or a burried waveguide) is used for optical wave propagation and an electrical transmission line (e. g. microstrip or coplanar waveguide)- for guiding the microwave, usually in the same direction. In the region where the electrical fields overlap, the optoelectronic interaction occurs. Note that a dc bias may additionally be applied to control the operating point. From a physical point of view the interaction is a nonlinear or active process. As discussed above, the photodetector and the laser diode are basic examples of two-port devices where optical power is converted into electrical power and vice versa. Typical three-port devices are electrically controlled optical modulators/switches or optically controlled microwave modulators/-switches. Due to the inherent nonlinearity these devices are further used for optoelectronic mixing of input electrical and/or optical signals where the output signal can be electrical or optical. As a result, such microwave optical interaction devices show a variety of optoelectronic functions where in special devices different functions may be achieved simultaneously.

A novel multifunctional device has recently been presented, the electroabsorption modulator integrated into the structure of a hetero-bipolar transistor (HBT), [19]. Such a device (Fig. 10) includes the common transistor characteristics as well as the modulator behaviour leading to a novel approach to optoelectronic integrated devices and circuits.

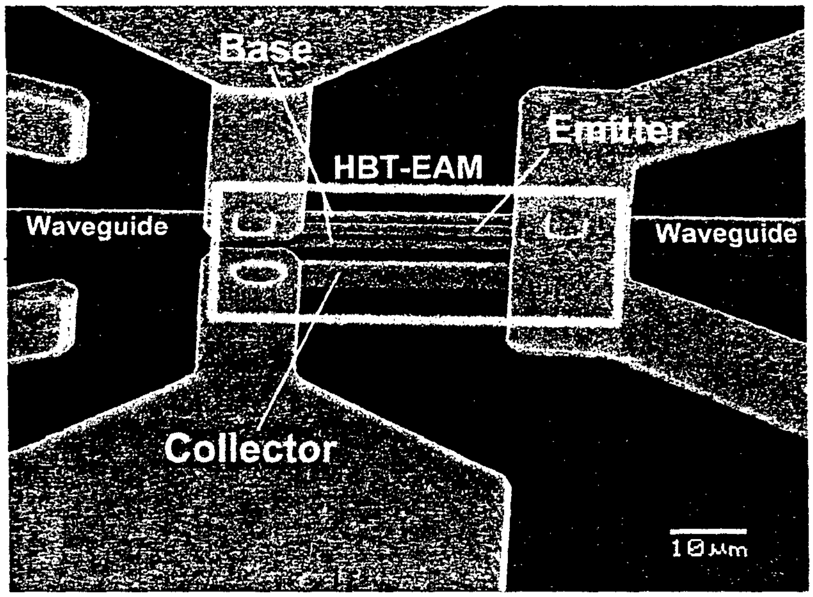

Fig. 10 SEM picture of an HBT-EAM

A further key integration technology is the optical coupling of the light between the optical waveguide and the external connection which usually is the optical fiber. This technique of fiber chip coupling includes the processing of V-grooves into the substrate or mother board and the tapering of the optical fiber [20] A further important technology is related to the adjustment and fixing of the fiber with respect to the optical waveguide. A result of measurement is shown in Fig. 11 where a coupling loss of less than 1 dB is achieved for a MFD of about 1.5 μm. It should finally be mentioned that high frequency electrical coupling of coplanar lines with coaxial connectors requires also a careful design of wire bonding.

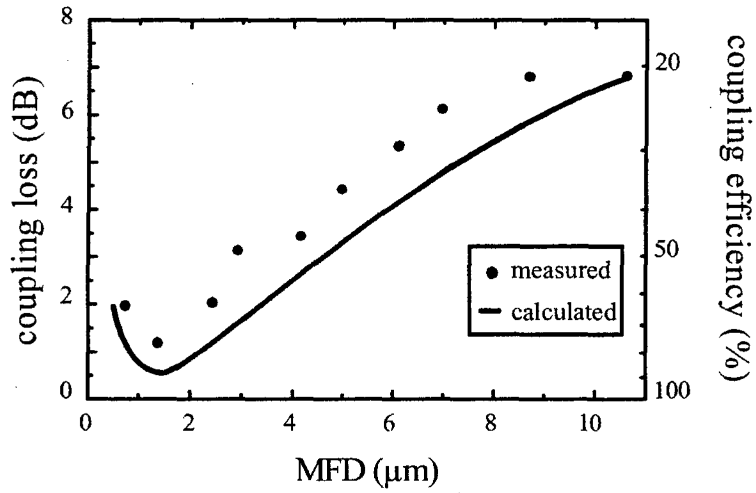

Fig. 11 Fiber chip coupling: coupling loss versus mode field diameter (MFD)

5. Photonic Microwave Signal Processing

In the following a few examples of optically controlled microwave devices and modules are discussed. The physical mechanisms are due to the optical generation of free charge carriers in a semiconductor leading to a control of some key electrical parameters determining the microwave properties.

5.1 Photonic microwave phase shifter/time delay control - In Fig. 12 electrical transmission lines- microstrip and coplanar – are sketched where the strip or the center conductor metal forms a Schottky contact with the semiconductor [6,7]. As a result the high capacitance per unit length gives rise to a slow mode behaviour and the electrical wavelength or the phase velocity are given by the width of the depletion region of the contact. This thickness of the space charge region furtheron depends critically on the applied reverse bias voltage (electrical control of the phase velocity and the delay time). When a fixed bias voltage is applied using an external series resistor, the voltage drop across the depletion layer can also be changed by absorption of an optical signal in the space charge region. As a result, the time delay is controlled optically and because it is a usual transmission line a true time delay shift occurs.

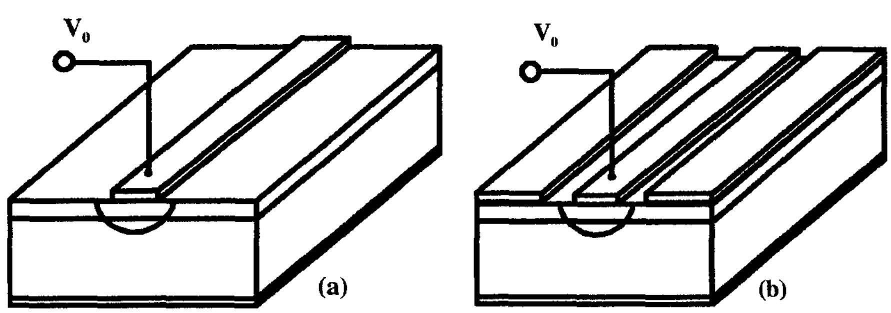

Fig. 12 Optically controlled phase shifter and time delay control using a Schottky contact microstrip line

5.2 Photonic ultrawide band (UWB) pulse generation - Fig. 13 elucidates an optically controlled generation of microwave pulses. The structure consists of a stripline resonator in the center with two gaps on each side. On the left hand side a dc or RF source is connected charging the resonator. On the right hand side an optoelectronic switch (OES) – the second gap - is provided which can optically be switched on in order to connect the output port of the resonator directly to an integrated antenna. Two operating scenarios can be distinguished: (i) Using a dc source the resonator is charged and by closing the OES a pulse is generated traveling to the antenna. The temporal width of the pulse is given by the length of the resonator (frozen wave generator). Please note that specific pulse forms are generated given by the structure of the charge line. (ii) Using a RF source the resonator is also charged and a standing wave of large amplitude, depending on the quality factor of the transmission line, is established. When the OES is optically closed, the standing wave will become a propagating wave and a short ultra broadband (UWB) pulse is generated and radiated using, for example, a broadband slot antenna [21,22]. This technique is a kind of pulse compression [23] known from nonlinear optics and soliton theory.

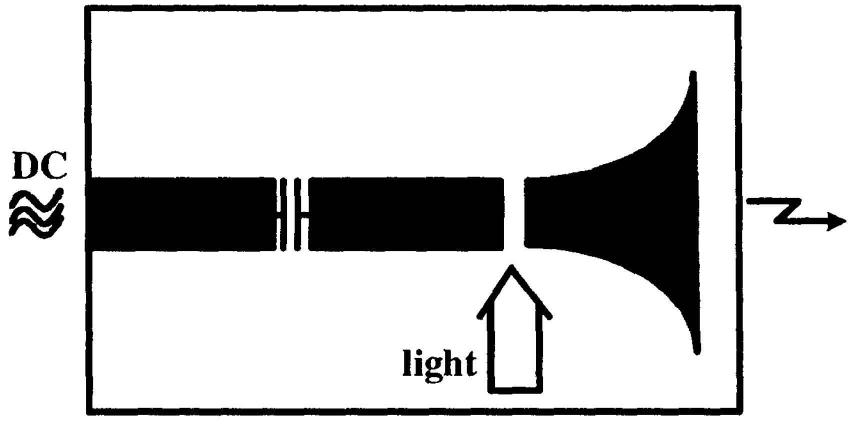

Fig. 13 Optoelectronic switching of a microwave resonator to obtain UWB signals

5.3 RF spectrum analyser - By using the techniques of 5.1 and 5.2 in an 2-dim or even 3-dim array parallel microwave signal processing becomes possible. Fig. 14 shows a microwave circuit where the input signal is divided into several channels and where each channel contains a time delay (T) and an amplitude (a) control using optical techniques as above mentioned. When the output signals are finally combined to a common connection a transversal filter results. In contrast, when the individual channels would be connected to antennas, a phased array antenna system results.

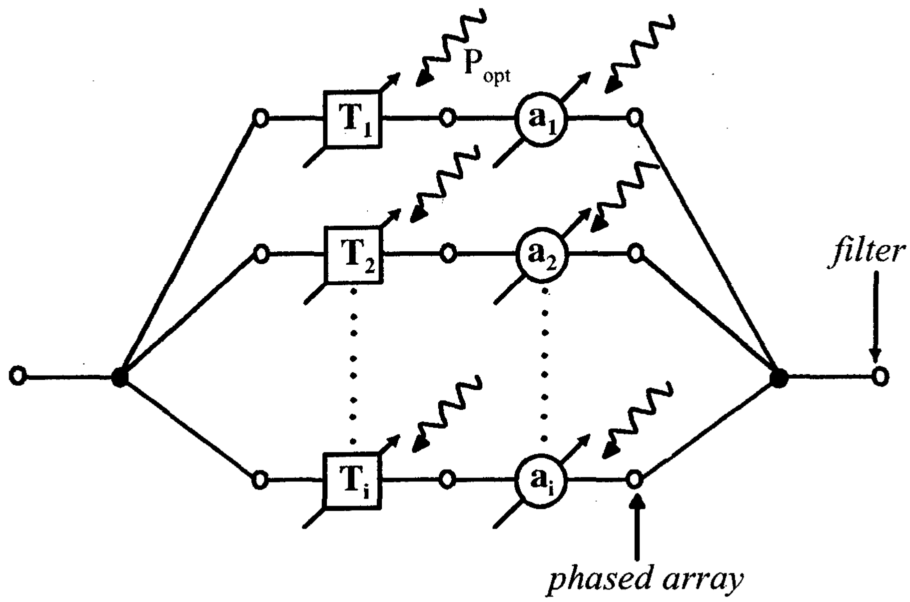

Fig. 14 Microwave signal processor

6. BROADBAND FIBER OPTICAL LINKS

An analog or digital - optical link consists of an optical transmission medium (preferably a fiber) and optoelectronic converters on both sides, see Fig. 15. The great advantage of such an optical link is that due to the broadband low-loss transmission capability the optical fiber (see Fig. 15) can ideally be used to transmit microwave signals and therefore replace other lossy metallic waveguides, see Fig. 16. Here different techniques have been explored. For example, on the transmitting side a cw laserdiode and an external modulator (electrooptic or EAM) and on the receiving side an optoelectronic photodetector can be used. Besides the bandwidth a key parameter of such a link is the link loss which depends on the conversion efficiencies of the optoelectronic elements, the optical coupling efficiencies and the attenuation and dispersion of the transmission medium [24]. Note that a link gain can easily be achieved when an optical amplifier (EDFA) and/or external modulators, preferably on both sides, are being used [24]. For high-speed and broadband operation the a. m. TW microwave photonic devices can succesfully be employed.

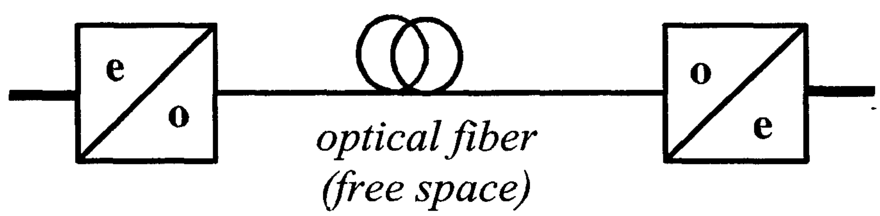

Fig. 15 Optical interconnection replacing an electrical cable

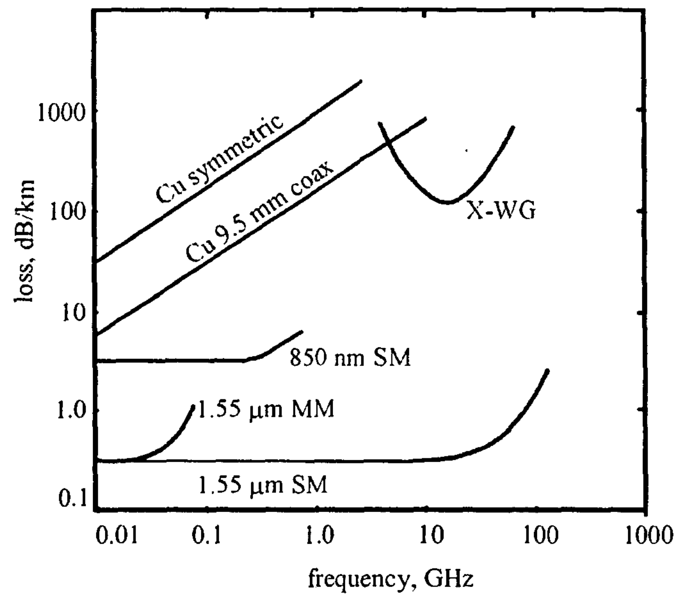

Fig. 16 Transmission loss of different transmission media

For bidirectional communications, as shown in Fig. 17, the link would require a duplication of the elements on both sides in order to provide uplink and downlink transmission. This is the conventional system architecture. But there is another solution using elements as above mentioned: Fig. 17 shows as an example also the advanced system where the base station contains only one optoelectronic element, here the transceiver, as realized by an EAT. Optically, the transceiver receives two signals, one for downlink purpose which is absorbed and one for the uplink which is modulated by the received electrical signal to be transmitted to the central station. Electrically the transceiver uses electrical frequency multiplexing saying that the up and downlink signals are at different frequencies. Given that due to the basic physical mechanisms the electrical bandwidth of the EAT is the same for the detection and the modulation process, a bandwidth of more than 170 GHz can be achieved using an TW EAT (Fig. 6).

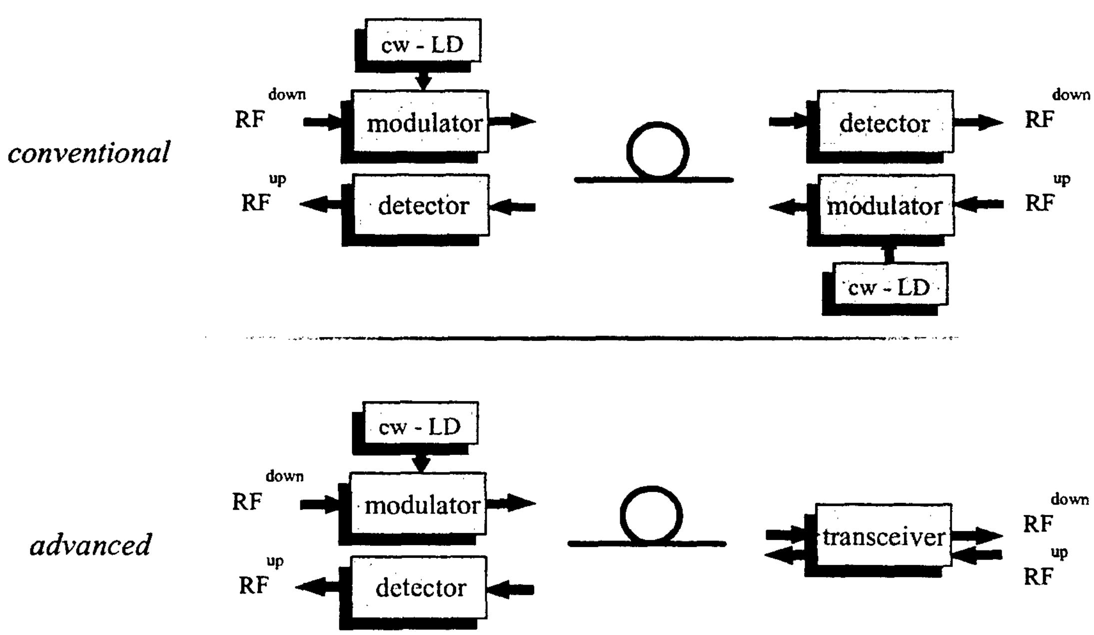

Fig. 17 Conventional and advanced IMDD scheme (IMDD is intensity modulation and direct detection)

7. MICROWAVE PHOTONIC SYSTEMS

Broadband fiber optic links are regarded to be basic building blocks for different microwave systems where specific advantages of the optical interconnections and optical signal processing capabilities are utilized. A few areas of significant applications are reviewed in the following.

7.1 Photonic local oscillators - Transmitting two optical wavelengths by using two frequency locked lasers or a two mode laser and mixing the two optical signals in a photodetector/-mixer emulates a microwave local oscillator where the difference frequency is photonically generated by heterodyne techniques and where wavelength tuning provides a bandwidth of several THz depending on the bandwidth of the detector [25]. Note also that an optically induced phase shift is directly transferred into the electrical domain. Fig. 18 shows a module fabricated for radioastronomical antennas; the module consists of a traveling-wave photomixer connected to a dc bias circuit with appropriate filters, a slot line antenna and a quasi optical lens to focus the radiated beam at 460 GHz into an He cooled SIS mixer.

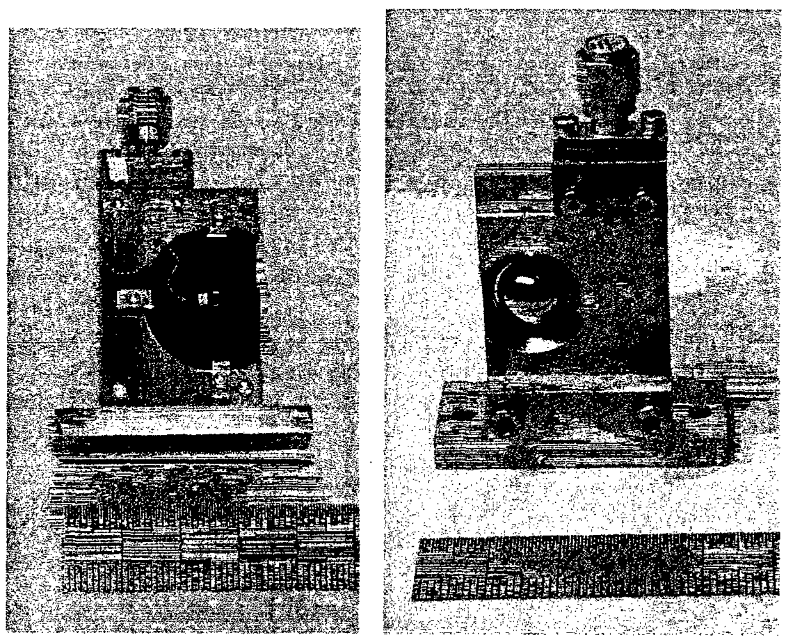

Fig. 18 Photograph of a photonic local oscillator module

7.2 EMC sensor - When the modulator at the end of a fiber is driven by an electrical input signal at the given position, the received optical signal can be used to measure the electrical signal quantitatively at the transmitter side and a field sensor results. Fig. 19 shows the circuit diagramme of such an E-field sensor for EMC applications. The sensor head consists of a dipole antenna. The output signal is fed into a transimpedance amplifier driving an EAM. The optical input signal at 1.55 µm is delivered by a laserdiode in the remote unit which contains also the photodiode to measure the output signal from the EAM in the sensor head. The dc bias for the amplifier as well as for the operating point of the EAM is provided by a photovoltaic cell (PVC) in the sensor head. A second laser diode in the read-out unit generates the necessary optical power.

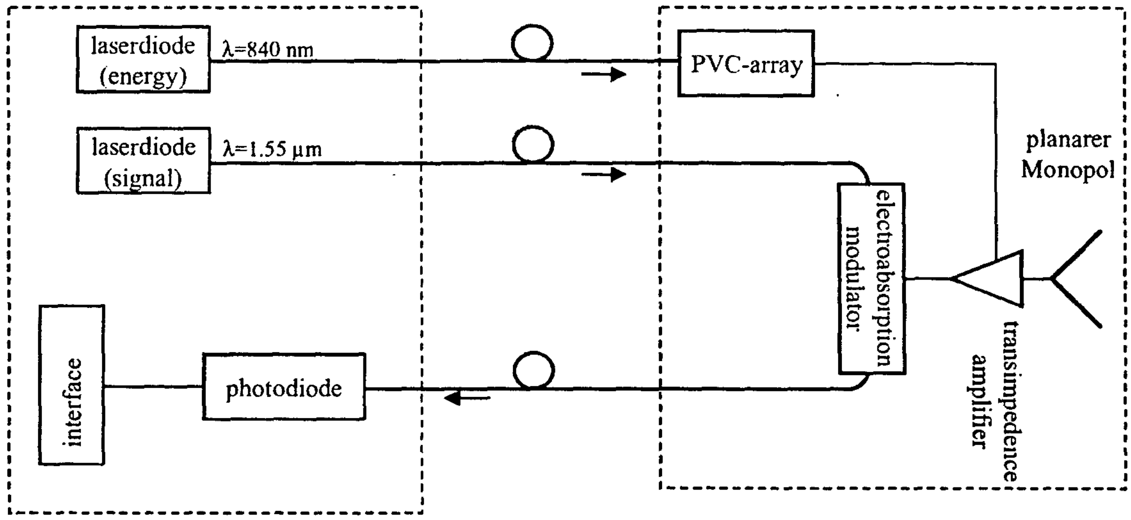

Fig. 19 EMC sensor [26,27]

7.3 Electrooptic sampling and optoelectronic testing - Using electrooptical properties of a semiconductor substrate (Fig. 20) an incoming optical beam is modulated by an applied electrical field and the reflected optical signal can be used to determine the electrical field at the position of the interaction. This set-up can directly be used to measure electrical fields, e.g. in integrated circuits, with high spatial resolution (2-dim field mapping, [28,29]) and without any mechanical contact. Moreover, characteristic sampling techniques have been presented where optical pulses in the pico- or femtosecond range are applied giving a measurement bandwidth in excess of 100 GHz. In a recently presented sensor, a microminiaturized modulator chip working in reflection mode and coupled to the end of a fiber has been applied to measure electrical fields in free space, again with high spatial resolution. Such a fiber sensor is used for contactless high-speed testing of integrated circuits or antenna radiation patterns [13] similarly to the EMC sensor mentioned before.

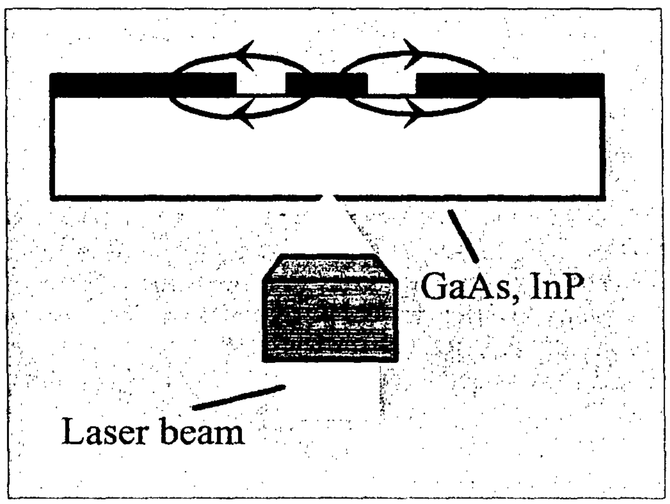

Fig. 20 Principle of electrooptic sampling

7.4 Hybrid fiber-coax (HFC) systems - In cable TV (CATV) techniques the RF signals received from TV satellites are converted into the optical domain and fed into a fiber to be transmitted over long distances with only small attenuation. The received optical signals are converted back into the electrical domain and guided to the costumer via coaxial cable. This HFC technique using again the advantages of the optical fiber transmission is continuously installed in major cities around the world where the uni-directional technique is replaced more and more by bi-directional links in order to establish a back channel, e. g. for multimedia applications.

7.5 Fiber-radio systems - It is agreed that fiber-radio access will provide a solution to the demands for a wireless connection to the costumer ("last or first mile problem"). For broadband services the frequencies are in the millimeterwave range, for example at 40 GHz or 60 GHz. Such a concept is based upon an optical link between the central office and the base stations in a picocellular structure which results from the high free space attenuation of the millimeterwave signal. As an example, 60 GHz fiber radio links have been demonstrated providing 155 Mbps and using EAMs for half-duplex and EATs for full-duplex transmission in a WDM ring network [30-32]. It is foreseen that for next generation broadband photonic communication networks, the electroabsorption modulator (EAM) and the electroabsorption transceiver (EAT) will be key elements. Experimentally, full duplex transmission in a WDM ring network and electrical frequency division multiplex (EFDM), as sketched in Fig. 21, have been studied. Here two CW LDs at different wavelengths are used to drive the modulator function of the EAT in each base station (BS) addressed by the optical wavelength (WDM technique). The other two LDs are externally modulated in the central station (CS) to provide the downlink transmission. These signals are absorbed in the EATs of the base stations to feed the wireless link. The electrical FDM technique is obvious from Fig. 17: downlink and uplink RF frequencies are 59.6 GHz and 60 GHz, respectively. The transmission quality at a data rate of 156 Mbps is finally determined and evaluated by a bit error rate tester (BERT).

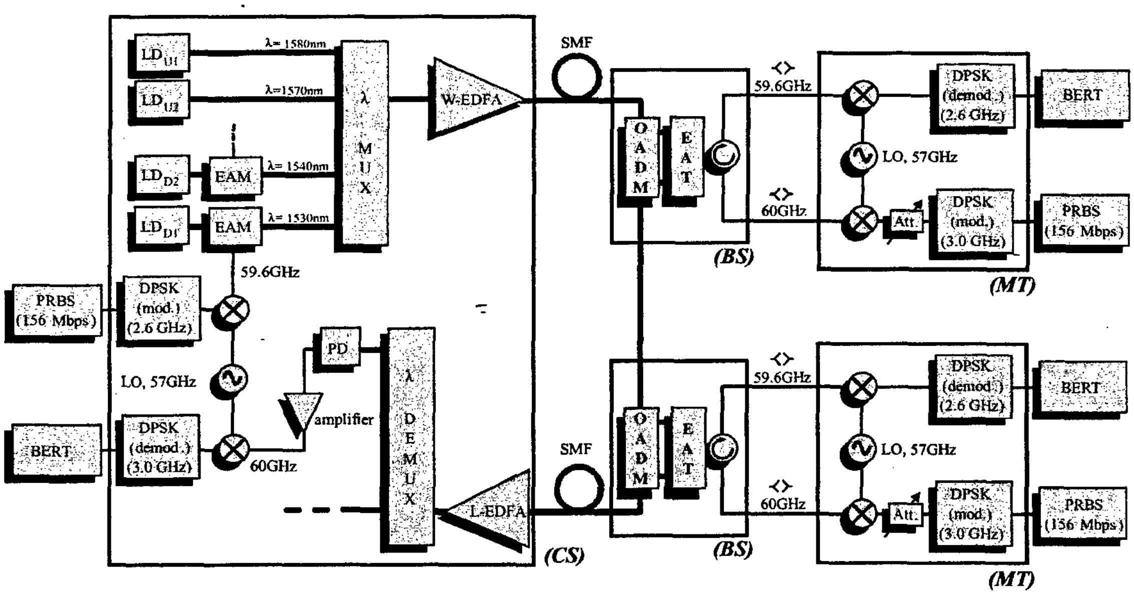

Fig. 21 Full-duplex 60 GHz mm-wave fiber wireless network employing an electroabsorption transceiver (EAT) as a key photonic component in the base station (BS)

7.6 Antenna systems – A major application of optical link technology is the remoting of antenna systems and, particularly, the optical control of array antennas, see for example

Refs. [33] and [34]. In the receiving mode a millimeterwave camera with photonic interconnection is obtained. Different applications in imaging are foreseen.

8. CONCLUSIONS

In the past decade the field of microwave and millimeterwave photonics has become a key technology extending from components and modules to systems with important applications The driver has been twofold: On one hand the broadband low-loss and high-speed transmision capability of optical fibers has led to a considerable interest in their use for distributing and controlling micro- and millimeterwave signals. On the other hand the breakthrough in the design and demonstration of several ultra-broadband photonic components has paved the way for wideband and high efficiency optoelectronic converters being important building blocks for microwave optical links. As a result, it can be foreseen that this multidisciplinary field of microwave photonics will continously be expanded and lead to further novel concepts due to the synergetic merging of different technologies.

In this contribution specific high-speed and broadband photonic components based upon the physics of electroabsorption have been discussed. In particular, electroabsorption modulators, photodetectors, mixers and transceivers have been presented. The multifunctional properties of the transceiver elements have been proven to be especially interesting. The performance of these elements has been demonstrated for example in a fiber-wireless WDM ring network by BER measurements; but the advantages will generally hold for other optical links with bi-directional transmission properties as well. The great advantage of this concept is that in the base station (in the sensor head or at the antenna side) just a single photonic component serves simultaneously as a converter for downlink and uplink communication and information transport. It is therefore concluded that these elements may play a significant and key role in fiber coupled wireless microwave and mm-wave networks and for high date rate transmission services such as in multimedia techniques.

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